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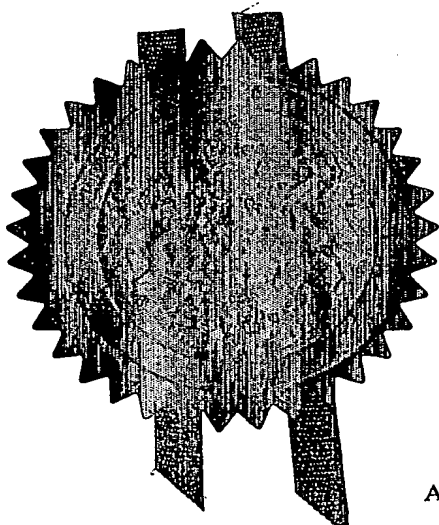
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25 Hale Street

Cambridge

CB4 3BZ

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DIGITAL SIGNAL PROCESSING WITH IMPROVED MAPPING

The invention relates generally to the field of digital signal processing and, in a particular example, to a method for obtaining an improved enhancement of the signal through improved mapping between the signal parameters and a set of alternative optimisation parameters in terms of which the signal enhancement is performed.

In general, signal enhancement involves applying one or more operations to the signal to improve the signal quality, for example, sharpening improves signal details, noise reduction removes signal noise.

While these methods do indeed produce enhanced signals, the quality of the resulting signal often varies depending on the signal content. For example, a maximum a-posteriori probability algorithm may produce pleasing results for a signal that contains structure on only a narrow range of linear scales. However, using the same algorithm may result in the undesirable appearance of oscillatory artefacts when applied to a signal that contains both sharp and smooth features. For example, an image of a human face contains both sharp features (e.g. wrinkles, and eyelashes) and smooth features (e.g. the cheeks and forehead). In the enhanced image the sharp features may be surrounded by spurious oscillations that contaminate the smooth features.

In the enhancement of a digital signal, the digitised data stream may be denoted by a vector \mathbf{d} containing N_d components, where N_d is the number of data samples. The data vector \mathbf{d} may be expressed as some function ϕ of the true digital signal \mathbf{s} that one wishes to enhance, i.e. $\mathbf{d} = \phi(\mathbf{s})$. The signal vector \mathbf{s} has length N_s , where N_s is the number of sample points at which the signal is estimated. The function ϕ can be non-linear and specifies the effect of the measuring apparatus on the signal. It is customary to consider the function ϕ in two parts: the predictable effect of the measuring apparatus on the signal \mathbf{s} ; and the stochastic noise part due to inaccuracies in the measurement process. One may thus write

$$\mathbf{d} = R(\mathbf{s}) + \mathbf{n}, \quad (1)$$

where R denotes the predictable response of the apparatus to the signal and \mathbf{n} is a vector of length N_d containing any stochastic noise contributions to the data vector.

5 In prior art, there exist signal enhancement algorithms for performing signal sharpening, noise reduction and other operations (see, for example Titterton D. M., 1985, *Astronomy & Astrophysics*, 144, 381). These algorithms provide an estimate \hat{s} of the underlying signal prior to its modification by the measuring apparatus and any addition of noise. The vector \hat{s} is termed the enhanced digital signal.

10 As a result of correlations between the pixels in the underlying digital signal, the effective number of degrees of freedom in the signal enhancement problem can be much smaller than the number of parameters in the signal vector s . This can lead to spurious artefacts and sub-optimal sharpening and noise reduction in the enhanced signal.

15 A number of approaches have been proposed to accommodate the problem of inter-pixel correlations. One approach (Gull S.F., 1989, in Skilling J., ed., *Maximum Entropy and Bayesian Methods: Developments in Maximum Entropy Data Analysis*, Dordrecht, pp 53-71) introduced the concept of an intrinsic correlation function (ICF) that is used to decorrelate the signal. The
20 ICF framework has been extended to allow reconstructions of objects on different scales (see Weir N., 1992, in *ASP Conf. Ser. 25: Astronomical Data Analysis Software and Systems I*, Vol. 1, pp 186), proposing a multi-channel approach, which allows for multiple scales of pixel-to-pixel correlations. In a pyramidal approach (see Bontekoe T.R., Koper E., Kester D.J.M., 1994,
25 *Astronomy & Astrophysics*, 284, 1037) the number of pixels retained in the low-resolution channels is decimated. Despite these improvements, choosing an ICF is not straightforward and employing suitable scale lengths and weights is of great importance. It is clear that there is no single set of ICFs that is universally optimal for all possible types of data.

30 Therefore, there remains a need to accommodate the problem of inter-pixel correlations in a way that is more broadly applicable.

Accordingly, the present invention consists in one aspect in a method for digital signal processing that includes describing the signal values as functions of a set of alternative optimisation parameters; selecting a mapping between the signal parameters and the optimisation parameters; determining
5 the quality of the mapping by evaluation of a mapping quality function; obtaining an optimum mapping by maximisation of the mapping quality function; providing a signal enhancement operation performed entirely in terms of the optimisation parameters; applying signal enhancement to the digital signal using the optimal mapping to produce an enhanced signal.

10 The present invention, in this aspect, has the advantage that the correlation structure of the signal itself determines the mapping between the signal parameters and the optimisation parameters in terms of which the signal enhancement is performed. The mapping provides an efficient means for representing the information content of the signal. By performing the
15 enhancement of the signal entirely in terms of optimisation parameters connected to the signal parameters by the optimal mapping, one obtains an enhanced signal in which the sharpening and noise reduction are substantially improved and the presence of spurious artefacts is greatly reduced.

The invention will now be described by way of example with reference
20 to the accompanying drawings, in which:

Fig. 1 is a flowchart illustrating one embodiment of the present invention; and

Fig. 2 is a flowchart illustrating a second embodiment of the present invention.

25 In the following description, the present invention will be described as a method implemented as a software program. Those skilled in the art will readily recognise that the equivalent of such software may also be constructed in hardware. Because signal enhancement algorithms and methods are well known, the present description will be directed in particular
30 to algorithm and method steps forming part of, or cooperating more directly with, the method in accordance with the present invention. Other parts of such algorithms and methods, and hardware and/or software for producing and

otherwise processing the signal, not specifically shown or described herein, may be selected from such subject matters, components, and elements known in the art. Given the description as set forth in the following specification, all software implementation thereof is conventional and within
5 the ordinary skill in such arts.

Fig. 1 illustrates a preferred embodiment of the present invention for processing a signal with a specific signal processing path in order to obtain an enhanced output signal. In general, the present invention performs an enhancement operation to a signal by describing the signal in terms of a set of
10 alternative optimisation parameters, determining the optimal mapping between the signal parameters and optimisation parameters; and performing the signal enhancement in terms of the optimisation parameters.

Referring to Fig. 1, there is shown a block diagram of the present invention. An input digital signal \mathbf{d} is obtained. Next, a mapping is selected
15 between the space of optimisation parameters \mathbf{h} and the signal parameters \mathbf{s} . This mapping may be expressed by the equation $\mathbf{s} = K(\mathbf{h}; \mathbf{p})$, where K is a function determining the mapping, the form of which may depend on a set of subsidiary mapping parameters \mathbf{p} . Next, the mapping quality function Q is evaluated. The value of the mapping quality function, possibly together with its
20 higher derivatives as a function of the mapping parameters \mathbf{p} , may then be used to guide the selection of new mappings. Next, from those values of the mapping parameters \mathbf{p} employed, the values of \mathbf{p} that yield the largest value of the mapping quality function are selected as the optimal mapping parameters $\hat{\mathbf{p}}$. The corresponding mapping $\mathbf{s} = K(\mathbf{h}; \hat{\mathbf{p}})$ is then selected as the
25 optimal mapping. Employing this optimal mapping, the signal enhancement problem now takes the form

$$\mathbf{d} = R(K(\mathbf{h}; \hat{\mathbf{p}})) + \mathbf{n}.$$

This equation may be recast in the standard form for a signal enhancement problem by defining the optimal response function \hat{R} as the composite of the
30 optimal mapping function K and the original response function R , thus $\hat{R}(\mathbf{h}) \equiv R(K(\mathbf{h}; \hat{\mathbf{p}}))$. The signal enhancement problem can therefore be written

as

$$\mathbf{d} = \hat{R}(\mathbf{h}) + \mathbf{n}, \quad (2)$$

which is directly analogous to equation (1), but is cast entirely in terms of the optimisation parameters \mathbf{h} and the optimal response function \hat{R} . Next, a signal enhancement operation is selected and applied to the signal enhancement problem defined by equation (2). The output of the signal enhancement operation will be a set of enhanced values $\hat{\mathbf{h}}$ for the optimisation parameters. Finally, the output enhanced digital signal $\hat{\mathbf{s}}$ is obtained by applying the optimal mapping function to the optimisation parameters, thus $\hat{\mathbf{s}} = K(\hat{\mathbf{h}}; \mathbf{p})$.

Referring to Fig. 1, the mapping operation may be entirely general, so that the signal parameters \mathbf{s} are some non-linear function of the optimisation parameters \mathbf{h} . The mapping parameters \mathbf{p} may be continuous and describe a continuously parameterisable mapping K . Alternatively, the mapping parameters \mathbf{p} may be discrete and act as labels for a set of pre-defined mappings.

In a preferred embodiment, the mapping between the signal parameters \mathbf{s} and the optimisation parameters \mathbf{h} is linear. In this case, the operation of the mapping K can be expressed in terms of a mapping matrix \mathbf{K} , so that the signal parameters \mathbf{s} may be expressed as $\mathbf{s} = \mathbf{K}(\mathbf{p}) \cdot \mathbf{h}$, where denotes the operation of matrix multiplication. This expression may be interpreted as the signal being a linear combination of the set of digitised basis vectors that make up the columns of the matrix \mathbf{K} , with the optimisation parameters \mathbf{h} acting as the coefficients in the linear combination.

Examples of the form of the digitised basis vectors include: sinusoidal functions, wavelet functions, Gaussian functions, top-hat functions, and signal-to-noise eigenfunctions. In the case in which the mapping parameters \mathbf{p} are discrete, they may act as labels for sets of pre-defined basis vectors. In the case in which the mapping parameters \mathbf{p} are continuous, they may act as controlling parameters for the form of some continuously parameterisable function that defines the shape of the digitised basis vectors. A specific

example of a useful continuously parameterisable function is that described by the equation

$$f(x) = A \left[1 + \frac{1}{n} \left(\frac{x^2}{x_0^2} \right)^{m/2} \right]^{-n},$$

in which the parameters A and x_0 determine respectively the amplitude and width of the basis function, and by varying the values of the indices m and n , the form of the function varies continuously and includes the specific forms of a top-hat, a Gaussian and a Lorentzian.

Returning to Fig. 1, once a mapping, and hence the values of the mapping parameters \mathbf{p} , has been chosen one must calculate the value of a mapping quality function $Q(\mathbf{p})$. This function may, in general, take any form. In any particular signal enhancement problem, whatever requirements exist on the properties of the final enhanced signal \hat{s} may be used to determine the nature of Q . The form of Q is chosen so that a final enhanced signal which more closely satisfies the requirements yields a larger value of Q . As an example, the value of Q may be defined so that a large value indicates the presence of fewer ringing artefacts in the enhanced signal

In a preferred embodiment, the quality mapping function $Q(\mathbf{p})$ will be the Bayesian evidence $\Pr(\mathbf{d} | H)$ of the input signal given the mapping adopted. The Bayesian evidence may be calculated using the equation

$$\Pr(\mathbf{d} | H) = \int_{\text{all } \mathbf{h}} \Pr(\mathbf{d} | \mathbf{h}, H) \Pr(\mathbf{h} | H) d\mathbf{h}.$$

In this equation the likelihood function $\Pr(\mathbf{d} | \mathbf{h}, H)$ describes the probability of obtaining the input data signal given any particular set of values for the optimisation parameters. The prior $\Pr(\mathbf{h} | H)$ codifies one's knowledge of the distribution of values for the optimisation parameters in advance of analysis of the data. The hypothesis H denotes the totality of assumptions regarding the signal enhancement problem and includes, for example, the assumed form of the response function R , the assumed statistical properties of the noise contribution \mathbf{n} . Most importantly, the hypothesis H also includes the mapping K used to relate the signal parameters \mathbf{s} and the optimisation parameters \mathbf{h} .

Thus the hypothesis H depends upon the mapping parameters \mathbf{p} , and we may take the mapping quality function to be $Q(\mathbf{p}) \equiv \Pr(\mathbf{d} | H(\mathbf{p}))$.

The practical evaluation of the evidence for any given set of mapping parameters \mathbf{p} can be computationally prohibitive for signal enhancement problems in which the number of optimisation parameters is large. In such cases, two complementary techniques in the prior art can be used to obtain an approximate value for the evidence. The first technique is to take samples from the distribution $\Pr(\mathbf{d} | \mathbf{h}, H) \Pr(\mathbf{h} | H)$ such that the number density of samples is proportional to the probability density of the distribution, possibly raised to some power. These samples can then be used to obtain an estimate of the evidence (see Gilks et al. 1995). The second technique employs a numerical optimiser to locate the maximum $\hat{\mathbf{h}}$ of the distribution $\Pr(\mathbf{d} | \mathbf{h}, H) \Pr(\mathbf{h} | H)$. The curvature matrix of the distribution is then calculated at the maximum point, and used to define a multivariate Gaussian approximation to the distribution. The corresponding volume of this multivariate Gaussian approximation can be calculated using Monte-Carlo evaluation of the curvature matrix determinant and yields an estimate of the evidence (see, for example, Hobson et al. 2002).

Returning to Fig. 1, alternatively or additionally, the signal enhancement operation may be noise reduction, de-blocking, scene balance adjustment, tone scale adjustment, colour re-mapping, signal interpolation, signal sharpening or any other operations with which one or more attributes of a signal can be enhanced.

In a preferred embodiment, the signal enhancement will be performed using the maximum a posteriori probability algorithm (see, for example Titterton, 1985). The optimal values of the optimisation parameters $\hat{\mathbf{h}}$ are taken to be those which maximise the joint probability distribution $\Pr(\mathbf{h}, \mathbf{d} | H)$, which is given by the equation

$$\Pr(\mathbf{h}, \mathbf{d} | H) = \Pr(\mathbf{d} | \mathbf{h}, H) \Pr(\mathbf{h} | H).$$

The likelihood function $\Pr(\mathbf{d} | \mathbf{h}, H)$ and prior $\Pr(\mathbf{h} | H)$ are as described above. In the prior art, it is usual to define the log-likelihood function $L(\mathbf{h})$ such that

$\Pr(\mathbf{d} | \mathbf{h}, H) = \exp[L(\mathbf{h})]$, and the regularising function $S(\mathbf{h})$ such that $\Pr(\mathbf{h} | H) = \exp[S(\mathbf{h})]$. The enhanced signal $\hat{\mathbf{h}}$ is then that which maximises with respect to \mathbf{h} the objective function

$$F(\mathbf{h}) = L(\mathbf{h}) + S(\mathbf{h}).$$

- 5 The location of the maximum point is determined using a numerical optimisation algorithm.

 If the signal enhancement is performed using the maximum a posteriori probability algorithm, then this solution will already have been obtained in the step in which the approximate value of the Bayesian evidence is calculated
10 using a multivariate Gaussian approximation, and so the formal signal enhancement step can be avoided, thereby speeding up the process.

 A preferred application of the present invention is to the enhancement of a digital image \mathbf{d} . Such an image may have been subjected to some de-sharpening by the imaging apparatus, denoted by the response mapping R ,
15 and also contain additional noise \mathbf{n} resulting from inaccuracies in the imaging process. The goal of the image enhancement procedure is to obtain an enhanced image $\hat{\mathbf{s}}$ that is a better representation of the original scene \mathbf{s} being imaged, by sharpening and de-noising the data image \mathbf{d} .

 A specific illustration of how the present invention may be applied to
20 this image enhancement problem is shown in Fig. 2.

 Referring to Fig. 2, in this illustration the mapping parameters \mathbf{p} are chosen to be discrete and act as labels for a set of pre-defined mappings. Each mapping is chosen to be linear such that $\mathbf{s} = \mathbf{K}(\mathbf{p}) \cdot \mathbf{h}$, where the symbol
denotes the operation of matrix multiplication. The specific example of such a
25 pre-defined set of mappings \mathbf{K} , as illustrated in Fig. 2, is a library of two-dimensional orthogonal inverse wavelet transforms, each based on a different mother wavelet. In each case, the optimisation parameters \mathbf{h} are then the coefficients of the corresponding digitised wavelet basis functions.

 For each wavelet transform from the library, corresponding to a
30 different value for a single discrete mapping parameter p , one then calculates the quality mapping function $Q(\mathbf{p}) \equiv \Pr(\mathbf{d} | H(p))$ based on the Bayesian

evidence. In the image enhancement application, it is preferable to estimate this quantity by employing a numerical optimiser to locate the maximum $\hat{\mathbf{h}}$ of the distribution $\Pr(\mathbf{d} | \mathbf{h}, H) \Pr(\mathbf{h} | H)$, and then calculate the curvature matrix of the distribution at this maximum point to define a multivariate Gaussian approximation to the distribution. The numerical maximisation of $\Pr(\mathbf{d} | \mathbf{h}, H) \Pr(\mathbf{h} | H)$ can be performed using standard optimisation algorithms, such as the conjugate-gradient, variable-metric or quasi-Newton techniques, or some hybrid method. The curvature matrix \mathbf{M} at the maximum can be approximated by calculating numerical second differences of the distribution. The volume of the corresponding multivariate Gaussian then gives an approximate value for the evidence,

$$\Pr(\mathbf{d} | H(p)) \approx (2\pi)^{N_h/2} |\mathbf{M}|^{-1/2} \Pr(\mathbf{d} | \hat{\mathbf{h}}, H) \Pr(\hat{\mathbf{h}} | H),$$

where N_h is the number of optimisation parameters. The determinant of the curvature matrix $|\mathbf{M}|$ in the above expression can be evaluated using a Monte-Carlo technique.

The wavelet transform $\mathbf{K}(\hat{p})$ from the library that yields the largest value of $\Pr(\mathbf{d} | H(p))$ is chosen as the required optimal mapping.

Returning to Fig. 2, in the preferred embodiment, the image enhancement will be performed using the maximum a posteriori probability algorithm. The optimal values of the optimisation parameters $\hat{\mathbf{h}}$, corresponding to the optimal mapping, are taken to be those which maximise the probability distribution $\Pr(\mathbf{d} | \mathbf{h}, H) \Pr(\mathbf{h} | H)$. These values will already have been obtained in the step in which the approximate value of the Bayesian evidence is calculated using a multivariate Gaussian, and so the final enhanced image is immediately obtained as $\hat{\mathbf{s}} = \mathbf{K}(\hat{p}) \cdot \hat{\mathbf{h}}$.

The subject matter of the present invention relates to digital signal processing technology, and in a preferred form provides technology that digitally processes a digital image to determine the optimal mapping between the signal parameters and a set of optimisation parameters and then utilises the results obtained in the further processing of the digital signal.

In other forms of the invention, there is provided a method of processing a digital signal, comprising the steps of selecting a mapping between the signal domain and an alternative optimisation domain in dynamic dependence on the signal; deriving an alternative signal representation from the digital signal using the selected mapping; and performing a signal processing operation on the alternative signal representation.

In this context, the signal domain is the domain of the signal parameters or signal values. The alternative signal representation is preferably in the form of a set of optimisation parameters as previously described. The optimisation domain is then preferably the domain of the optimisation parameters, in which the signal processing operation is performed.

The term "in dynamic dependence on" preferably means in dependence on an appropriate unit of the signal, with a mapping being selected for each such unit. For example, in an image processing application, the mapping is preferably selected in dynamic dependence on an image represented by the signal. Alternatively, it may be selected in dynamic dependence on a block of pixels within an image, for example a block of eight by eight or thirty-two by thirty-two pixels. Other block sizes may, of course, be used.

Advantageously, the mapping is selected from a plurality of candidate mappings by evaluating and preferably maximising a mapping quality function which provides an indication of the quality of a given candidate mapping.

The present invention may be implemented for example in a computer program product. A computer program product may include one or more storage media, for example, magnetic storage media such as magnetic disk (such as a floppy disk) or magnetic tape; optical storage media such as optical disk, optical tape, or machine readable bar code; solid-state electronic storage devices such as random access memory (RAM), or read-only memory (ROM); or any other physical device or media employed to store a computer program having instructions for controlling one or more computers to practice the method according to the present invention.

CLAIMS

1. A method of processing a digital signal, comprising the steps of selecting a mapping between the signal domain and an alternative optimisation domain in dynamic dependence on the signal; deriving an alternative signal representation from the digital signal using the selected mapping; and performing a signal processing operation on the alternative signal representation.
2. A method according to Claim 1, wherein the mapping is selected from a plurality of candidate mappings by evaluating a mapping quality function which provides an indication of the quality of a given candidate mapping.
3. A method according to Claim 2, wherein the mapping is selected by maximising the mapping quality function.
4. A method according to Claim 3, wherein the plurality of candidate mappings are defined by a set of one or more mapping parameters; and wherein the mapping quality function is maximised as a function of the mapping parameters.
5. A method according to any of Claims 2 to 4, wherein evaluating the mapping quality function comprises performing the signal processing operation.
6. A method according to any of the preceding claims, wherein the signal processing operation is a signal enhancement operation.
7. A method according to any of the preceding claims, wherein the alternative signal representation is in the form of a set of optimisation parameters.

8. A method for processing a digital signal, comprising the steps of:
 - a) describing the signal values as functions of a set of alternative optimisation parameters;
 - b) selecting a mapping between the signal parameters and the optimisation parameters;
 - c) determining the quality of the mapping by evaluation of a mapping quality function of a set of mapping parameters;
 - d) obtaining an optimum mapping by maximisation of the mapping quality function as a function of the mapping parameters;
 - e) providing a signal enhancement operation performed entirely in terms of the optimisation parameters;
 - f) applying signal enhancement to the digital signal using the optimal mapping to produce an enhanced signal.
9. The method claimed in Claim 8, wherein the mapping parameters are continuous and describe a continuously parameterisable mapping.
10. The method claimed in Claim 8, wherein the mapping parameters are discrete and act as labels for a set of pre-defined mappings.
11. The method claimed in Claim 8, wherein the mappings are general non-linear functions.
12. The method claimed in Claim 8, wherein the mappings are linear functions.
13. The method claimed in Claim 8, wherein the optimisation parameters are selected from the group consisting of coefficients of sinusoidal functions; coefficients of wavelet functions; coefficients of Gaussian functions; coefficients of top-hat functions; coefficients of signal-to-noise eigenfunctions of the input signal; coefficients of continuous parameterisable functions that vary continuously between two or more standard forms.

14. The method claimed in any one of Claims 8 to 13, wherein the mapping quality function is the Bayesian evidence of the input signal given the selected mapping.
15. The method claimed in any one of Claims 8 to 14, wherein the signal enhancement operation is selected from the group consisting of sharpening; noise reduction; tone scale adjustment; intensity balance adjustment; colour balance adjustment; colour re-mapping; de-blocking and image magnification employing interpolation.
16. A computer program product for performing the method of any one of the preceding claims.
17. Digital signal processing apparatus comprising analysis means for digitally processing a digital image represented by signal parameters to determine the optimal mapping between the signal parameters and a set of optimisation parameters; and processing means adapted to utilise said optimal mapping in the further processing of the digital signal.
18. Digital signal processing apparatus according to Claim 17, wherein said analysis means serves to describe the signal parameters as functions of a set of alternative optimisation parameters; select a mapping between the signal parameters and the optimisation parameters; determine the quality of the mapping by evaluation of a mapping quality function of a set of mapping parameters; and obtain an optimum mapping by maximisation of the mapping quality function as a function of the mapping parameters.

ABSTRACT

DIGITAL SIGNAL PROCESSING WITH IMPROVED MAPPING

A method of performing a signal enhancement operation on a digital input signal is described. The method produces a best estimate of a true signal which the digital input signal is assumed to represent. The method involves deriving a plurality of candidate mappings, each defining a mapping between the signal domain of the digital input signal and an alternative optimisation domain, each signal in the signal domain corresponding to a set of optimisation parameters in the optimisation domain. For each candidate mapping, an indicator of the quality of the candidate mapping is calculated and a set of optimisation parameters in the optimisation domain of the candidate mapping is generated, the set of optimisation parameters representing an enhanced signal in that domain. The highest-quality mapping is then selected in dependence on the calculated indicators, and the set of optimisation parameters generated for the selected mapping is selected. The selected mapping is applied to the selected set of optimisation parameters to produce an enhanced digital signal. The method finds application in a variety of signal processing fields including image processing, and is applicable, for example, to image processing tasks such as image enhancement or image reconstruction.

(Figure 1)

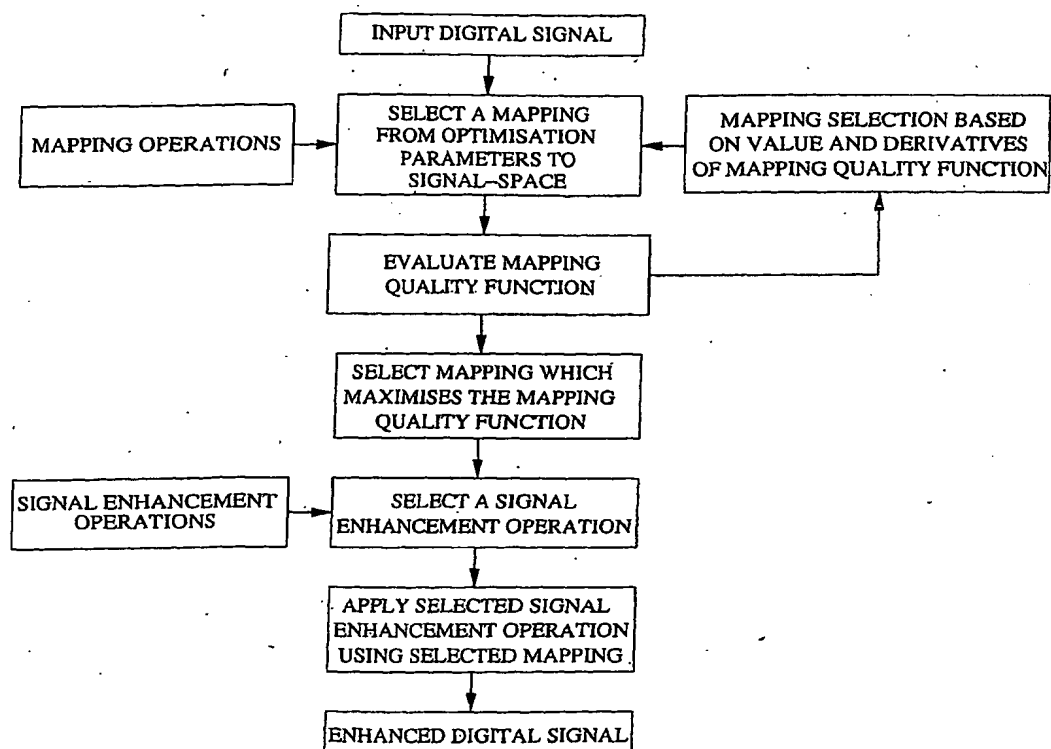


Figure 1:

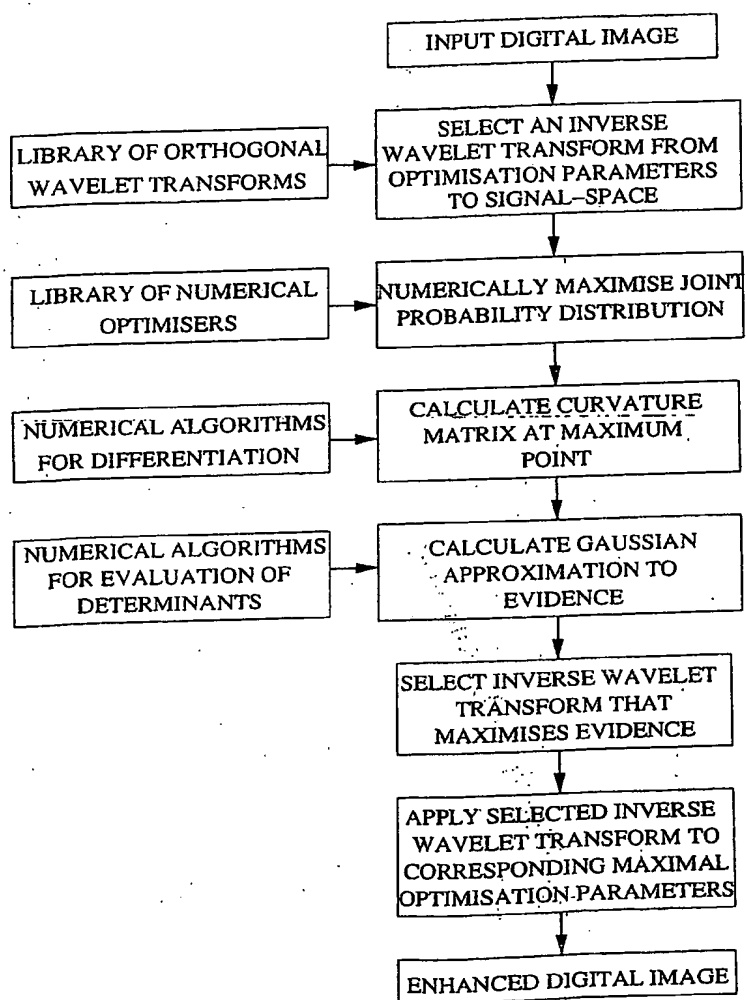


Figure 2: